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FACTORS AFFECTING THE LOW ACHIEVEMENT OF UTILIZATION EFFICIENCY OF WAVE ENERGY FOR ELECTRIC POWER PLANT WITH TAPERED CHANNEL TECHNOLOGY

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ABSTRACT: Ocean waves is one of the alternative sources of renewable energy that widely available on earth. Attempt on conversion of wave energy into electric power has a lot to do, but it is still constrained by the low achievement of utilization efficiency. This paper presents the results of physical model research regarding the factors affecting the efficiency achievement of the design of Baron Wave Power Plant with Tapered Channel (Tapchan) technology. The model investigation was conducted on 15 m x 20 m size of three dimensional wave basins in The Applied Hydraulics Laboratory Department of Civil and Environmental Engineering Gadjah Mada University. Tapchan model was built based on the design drawings and field data survey in the geometric scale of 1:25. The models were simulated with 3 kinds of wave direction (175°; 191° and 210°) where the designed center line of tapered channel at the direction of 178°. Nine variations of wave height and period in 3 kinds of water depth (LWL, MSL, and HWL) were used to simulate the models. The results indicate that the low performance efficiency was only about 1% -14% or an average of 7% and much influenced by main factors, namely the collector wall geometric, the alignment of channel direction with the incoming wave direction and the magnitude of wave deformations at the bay.

Keywords: Wave energy, tapered channel, low efficiency, wave deformation.

INTRODUCTION

Indonesia as a maritime country with vast sea more than 70% of the total area has the potential of considerably large renewal energy sources that exist in the oceans. Renewable energy sources include ocean waves, tides, thermal energy and ocean current energy. Wave power plant is a power plant that use wave energy and convert it into mechanical motion to generate electricity. The amount of energy generated depends on the length, height and velocity of the wave. Utilization of ocean wave energy technology is now still being developed including the buoy system, oscillating water column, and tapered channel.

Along with the depletion of fossil energy sources as an unrenewable energy source which is used until now, then it is time the Indonesian government explores other energy sources. By noticing the potentials and problems, Center for Assessment and Application of Technology (BPPT), the Ministry of Research and Technology in 1997 cooperated with Indonor developed a pilot project planning Wave Power Plant (PLTG) of type Tapered Channel in Baron, Yogyakarta. Tapered Channel technology using concept as shown in Figure 1 is one of technique that utilizes potential energy of sea water by channeling the wave propagation into narrowed channel then expecting the wave heightened and the overflowing water is lodged into a higher elevation reservoir. Thus, the water that accommodated in the reservoir is a power which can be mobilized to generate electricity.

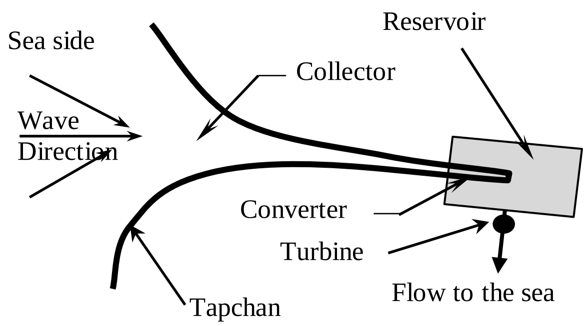

Figure1. Concept of wave energy utilization for electric power plant by Tapered Channel (Tapchan).

The input power expected to be mobilized is energy flux of wave propagating into tapchan channel through the collector and converter. In their propagation into tapchan, the waves will be disrupted in the bay and in the collector so that the amount of energy expected to get to the reservoir or the converter will be reduced. How big is the energy reduction or how much power inputs can be used is a question that needs an answer. Unfortunately, the results of the physical model test showed the achievement of efficiency was small enough that only

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about 1% -14% or an average of 7% (Triatmadja et al. 2010). This paper presents the empirical facts and the factors that lead to low performance efficiency obtained in the physical model test study conducted by the authors.

WAVE ENERGY

Based on the small-amplitude wave theory, the total energy contained in wind waves is the sum of kinetic energy and potential energy (US Army Corps of Engineer, 1984; Dean and Dalrymple, 1991; Triatmodjo, 1996). The wave kinetic energy is energy caused by the velocity of the water particles due to the wave motion.

Based on the theory of small-amplitude waves, for sinusiodal waves the magnitude of the kinetic energy per unit wavelength per width unit is obtained from the equation:

$$E_k=\int_0^L \int_{-d}^0 \tfrac{1}{2}\,\rho\, dxdy(u^2+y^2) \qquad (1)$$

$$u = \left[\frac{\pi H}{T}\right]\left[\frac{\cosh k(d+y)}{\sinh kd}\right]\cos(kx-\sigma t)$$

$$v = \left[\frac{\pi H}{T}\right]\left[\frac{\sinh k(d+y)}{\sinh kd}\right]\sin(kx-\sigma t)$$

By solving the equation (1), hence, the kinetic energy of a single wave per unit width gained by:

$$E_k=\frac{\rho g H^2 L}{16} \qquad (2)$$

While the potential energy is the energy generated by the movement of the water level due to the wave exists. Potential energy per wave crest width per wavelength unit is obtained from the equation:

$$E_p=\int_0^L \rho g(d+\eta)\frac{(d+\eta)}{2}dx-\rho g L H(d/2) \qquad (3)$$

with:

$$\eta = \frac{H}{2}\cos(kx-\sigma t)$$

By solving the equation (3), thus obtained:

$$E_p = \frac{\rho g H^2 L}{16} \qquad (4)$$

Hence, the total energy per unit width can be calculated by summing the kinetic energy and potential energy mentioned above which is equal to:

$$E=E_k+E_p=\frac{\rho g H^2 L}{16}+\frac{\rho g H^2 L}{16}=\frac{\rho g H^2 L}{8} \qquad (5)$$

Wave energy is transformed from one point to another along one wavelength, so that the average energy per unit area is as follows:

$$\overline{E}=\frac{E}{L}=\frac{\rho g H^2}{8} \qquad (6)$$

Where:

$\overline{E}$ = the average energy per unit area (Nm/m^2);

H = H_{rms}= root-mean-square wave height;

$H_{rms} = \frac{1}{N}\sqrt{\sum_{i=l}^{N} H_i^2}$, where N = the amount of data.

Wave reaching the beach and hitting coastal structures such as Tapchan, then some wave energy will be reflected and some will spread down the channel. According to Dalrymple (1991) in Triatmadja (2010), the amount of energy reflected and transmitted depends on the wave characteristics such as height and period, type of structure (potrositas and roughness), the geometry of the structure (slope, height and width) and the surrounding environment (the depth of water and the contours of the coast bed). Energy transferred (energy flux) is often referred to as wave power (P), that is the wave energy per time unit which contained or dispersed in the direction of the wave propagation. The average energy flux per width unit is:

$$\overline{P}=\overline{E}\,.\,n.\,c = \overline{E}\,.\,C_g \qquad (7)$$

Assumed that the energy flux is constant:

$$(\overline{E}\,.n.\,c)_1 = (\overline{E}\,.n.\,c)_2 \qquad (8)$$

$$n=\frac{1}{2}\left(1+\frac{2kd}{\sinh 2kd}\right) \qquad (9)$$

$$C=\frac{2gT}{2\pi}\tanh(2kd) \qquad (10)$$

$$L=\frac{2gT^2}{2\pi}\tanh(kd) \qquad (11)$$

Where: Cg = velocity of the wave group (m/dtk).

Wave reaching the beach and hitting coastal structures such as Tapchan, some wave energy will be reflected and some will spread down the channel. Under the law of Conservation of Energy, the magnitude of the energy flux average is:

$$P_i = P_r + P_t \qquad (12)$$

$$P_i=\frac{1}{8}\cdot g\cdot H_i^2\cdot C_{gi} \qquad (13)$$

$$P_r=\frac{1}{8}\rho\cdot g\cdot H_r^2\cdot C_{gr} \qquad (14)$$

$$P_t=\frac{1}{8}\rho\cdot g\cdot H_t^2\cdot C_{gt} \qquad (15)$$

Assumed that the energy flux is constant:

$$\left(\overline{E}.n.C.b\right)_i=\left(\overline{E}.n.C.b\right)_r+\left(\overline{E}.n.C.b\right)_t \qquad (16)$$

Subscript i, r and t indicate the incoming wave, wave reflection and wave transmission respectively. Sketch of the incoming wave, wave reflection and transmission of wave can be seen in the picture below.

The wave hitting the vertical and watertight wall will be reflected perfectly with perpendicular direction against the wall which can be determined from the superposition of two waves having the same wave numbers, periods and amplitudes but in opposite direction. In the small-amplitude wave, the elevation of water level above the water level for incoming wave and reflected wave is defined as follows (Dean, R.G.,1984 in Triatmadja et al, 2010).

Incoming wave:

$$\eta_i = \frac{H_i}{2} \cos (kx - \sigma t) \quad \text{.......................................(17)}$$

Reflected wave:

$$\eta_r = \frac{H_i}{2} \cos (kx + \sigma t) \quad \text{.......................................(18)}$$

Where: $H_i/2 = H_r/2 = a$ (wave amplitude).

The combined water level elevation for incoming wave and reflected wave can be described as follows:

$$\eta = \eta_i + \eta_r = 2a \cos kx \cos \sigma t \quad \text{..............................(19)}$$

The equation above shows the water level fluctuations of perfect standing waves (klapotis) which periodic against space and time.

According to Horikawa (1978), if two waves with the same period but in the opposite direction having amplitudes ai and ar, where ai> ar, hence, the combination of the water level profiles of the waves are:

$$\eta = a_i \cos (kx - \sigma t) + a_i \cos (kx + \sigma t)$$

$$\eta = (a_i+a_r)\cos kx.\cos \sigma t + (a_i-a_r)\sin kx.\sin \sigma t \quad \text{..........(20)}$$

Wave energy flux going into Tapchan can be calculated from the amount of wave energy captured at the mouth of the collector. The amount of the energy is influenced by the characteristics of wave having different period, the direction of the incoming wave, the magnitude of the wave reflection that occurs in the mouth of the collector.

Furthermore, from the energy generated by the wave, the flux magnitude of the wave energy called the input force can be known. The wave energy flux can be calculated using the following equation:

1. The direction of the incoming wave is perpendicular against the model

$$\overline{P} = \frac{\rho \cdot g \cdot H^2 C_g \cdot b}{8} \quad \text{.......................................(21)}$$

2. The direction of the incoming wave makes an angle with tapchan as

$$\overline{P} = \frac{\rho \cdot g \cdot H^2 C_g \cdot b \cdot \cos\alpha}{8} \quad \text{..............................(22)}$$

POWER IN THE RESERVOIR

Power in the reservoir due to the potential energy derived from water runoff from the converter and then into the reservoir. This power is called the power *output*. Reservoir in Tapchan is not used to store water for a long time but to level the output, in other words as an input to prepare a stable water supply for the turbine.

If P_{rsv} (m kg / sec) is the potential energy being stored in the reservoir and having height by h (m), as well as the capacity to perform the discharge of Q (m3/dtk). Hence the amount of reservoir forces according to Dandekar, MM and Sharma, KN (1991) in Triatmadja et al (2010), can be expressed as follows:

$$P_{rsv} = Q.\rho.g.h_{rsv} \quad \text{..(23)}$$

$$Q = \frac{v}{t} \quad \text{..(24)}$$

Where: P_{rsv} = reservoir forces (m kg/dtk); Q = discharge, volume being store per time unit (m^3/dtk); ρ = water mass density (1000 kg/m^3); g = gravitational acceleration (9.81 m/dtk^2); H_{rsv} = height from *SWL* to the brink of the converter (m).

Equation (23) can be determined in horsepower unit (HP) as follows:

$$P_{rsv} = \frac{1000 \cdot Q \cdot h}{75} = 13.33 \cdot Q \cdot h \text{ (HP)} \quad \text{.....................(25)}$$

$$P_{rsv} = 0.736\ (13.33)\ .\ Q\ .\ h$$

$$P_{rsv} = 9.8\ Q.\ h \text{ (Kw)} \quad \text{.......................................(26)}$$

TAPCHAN EFFICIENCY

In accordance with the purpose of this study, the Tapchan efficiency can be calculated analytically by comparison of output power and input power. Output power is power occurred in reservoir or power coming into reservoir due to the water runoff from converter. While the input power is power caused by wave (energy flux) or power gained in the collector mouth. Tapchan efficiency can be calculated using the equation below (FT-UGM, 1971 in Triatmadja et al, 2010):

$$\eta = \frac{Power_{output}}{Power_{input}} \times 100\%$$

$$\eta = \frac{Q \cdot \rho \cdot g \cdot h_{rsv}}{\frac{1}{8} \rho \cdot g \cdot H^2 \cdot C_g \cdot b} \times 100\% \quad \text{.............................(27)}$$

Where: η = Tapchan efficiency (%);

Q = discharge or volume being stored pe time unit (m^3/dtk); b = width of channel being observed (m); ρ = water mass density (1000 kg/m^3); g = gravitational acceleration (9.81 m/dtk^2); γ = ρg.

METHODOLOGY

The study was conducted using a simulation of physical models at a geometric scale of 1:25 using the 3D wave basin facility 15 m x 20 m dimension in The Applied Hydraulics Laboratory (Coastal Engineering) Department of Civil and Environmental Engineering Gadjah Mada University (UGM). Structure model of the Tapered Channel are made from composition of steel plate and acrylic. Wave generator made from a wave board with dimension of 5 m x 0.5 m is equipped with a motor, and eccentricity control devices with the ability 0:00 to 0:30 m, variator control panel (wave period) and stroke as wave height controller. Instrument of wave height recorder (*wave syntheziser*) is equipped with Analog Digital Converter (ADC) for fluctuation data acquisition of water level through electrical resistivity sensor. Simulation was conducted with 3 types of incoming wave angles (175º, 191º, 210º), 3 different positions of water level (HWL, MSL, LWL) and 9 types of wave period and height. Figure 2 presents the layout of physical simulation model in this study. Wave height data were measured at 4 locations: in front of the bay (deep sea), in the bay, inside the collector and in the converter mouth. One measured point at the sea in front of the bay, 22 points inside the bay, 5 points inside the collector, dan one point at the converter mouth. A total of 272.160 water level elevation data were recorded and has been analyzed become 4.200 wave height (H) and the reservoir volume or discharge (Q) ranging from 675 data further trimmed to 2.520 data of $H_{average}$ and $Q_{average}$ around 45 data. The observation of water level in reservoir was conducted in 15 minutes for each running by recording the height reading every minute.

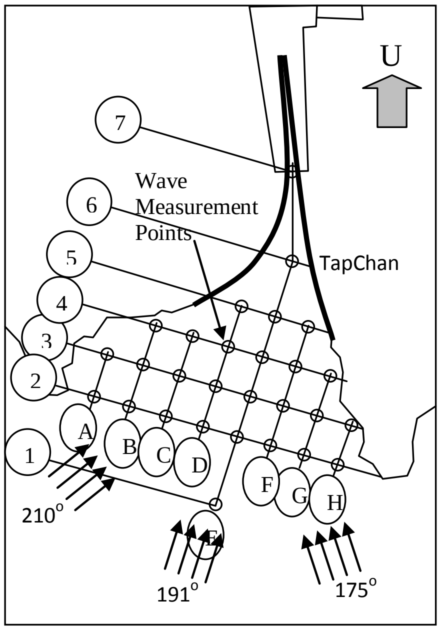

Figure.2. Layout of wave height measurement in model test (UGM-BPPT, 2006).

The wave deformation in the bay and inside the collector for 3 types of incoming waves resulted in the model are presented in form of water level fluctuation contour map in Figure 3, Figure 4, and Figure 5.

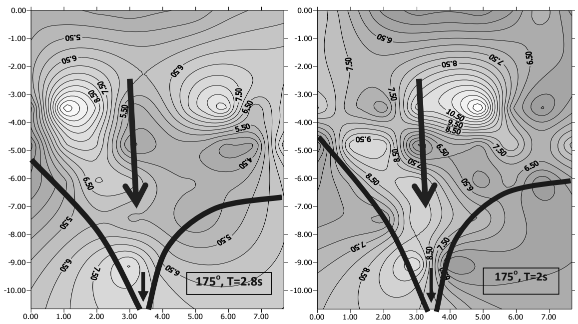

Figure 3. Wave deformation for T=2s & T=2.8s in wave direction of 175º.

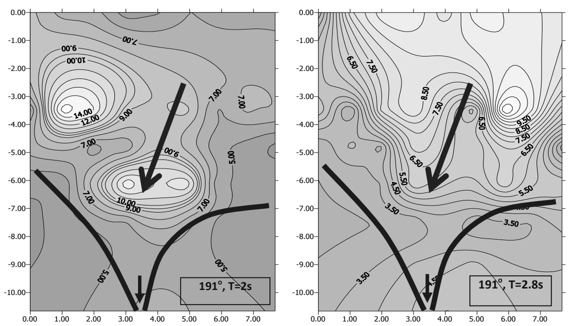

Figure 4. Wave deformation for T=2s & T=2.8s in wave direction of 191º.

RESULTS AND DISCUSSION

Incoming Direction & Wave Deformation

The test results obtained two kinds of data which are wave height data and water volume stored inside the reservoir. The wave energy expected to be captured into the collector mouth are waves that propagate in through the bay which will experience energy reduction due to wave deformation occurred at the site. Thus the information on the change of wave height and wave deformation is very important in determining the tapchan efficiency.

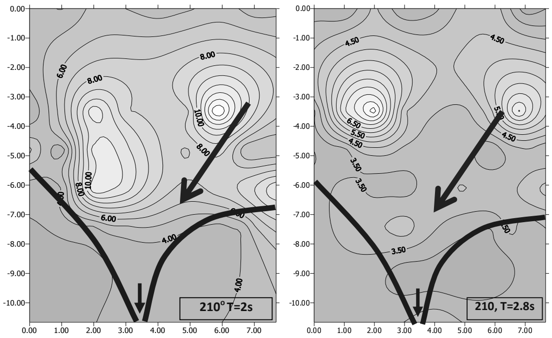

Figure 5. Wave deformation for T=2s & T=2.8s in wave direction of 210° (UGM-BPPT, 2006).

In Figure 3 to Figure 5 it can be seen that the wave height in the bay and the collector have significant deformation due to reflection, diffraction and wave breakup. Wave reflections from the bay wall meets the incoming wave causing a standing wave as shown in the image contours. Despite the bay wall, the collector wall also shows reflection waves for some direction of incoming waves.

The Effects of Wave Direction & Deformation

The wave deformation occurs as described above led to a small average of wave height (H) which up unto the converter mouth as shown in Figure 6. Amount of *H* obtained is only around 2,3H_0 for incoming angle 175°; 1,2H_0 for incoming angle 191° dan 1,4H_0 for incoming angle 210°. Those wave heights are smaller than the expected wave heights based on the theory which ranges around 3-4H_0.

The wave deformation occurrence in the bay area causing the energy flux that can be passed to the reservoir becomes very small.

Figure 7 presents the calculation result of the reduction of Wave Enegy Flux (*Fe*) value in the collector mouth and converter from original *Fe* in the bay mouth. From Figure 7 shown that 100% of *Fe* value in the bay mouth is fluctuating consecutively which is increase drastically to 268% in the collector mouth and then decrease drastically to 13,6% in converter mouth for incoming wave angle 175°. For incoming angle 191° & 210° decrease to 23,7% dan 19,3% respectively in the collector mouth and 2,2% dan 1,2% respectively in the converter mouth for MSL condition.

The relation of water volume entering the reservoir for each wave period (T) with time (t) is presented. From the data can be determined the discharge average (Q average) for each sea wave characteristic. Figure 8 shows the relation of Q and H_o/L_o for 3 type of wave directions being tested in MSL condition.

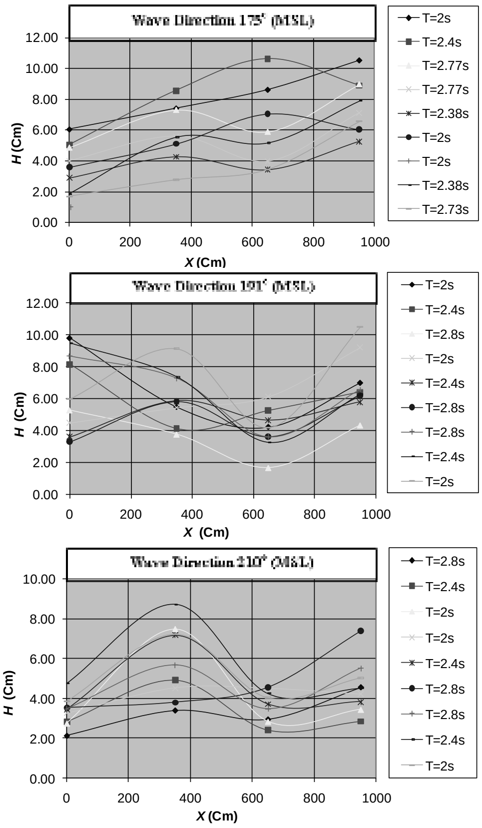

Figure 6. Wave height changes from bay to converter for 3 wave direction (175°; 191°; 210°) in MSL condition (UGM-BPPT, 2006).

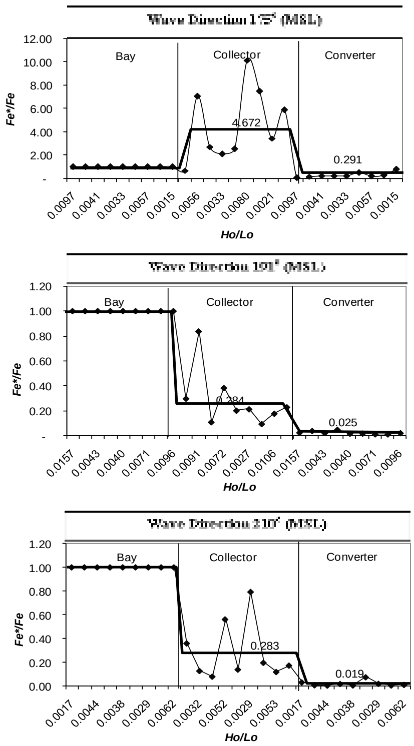

Figure 7. Flux energy changes from bay to converter for 3 wave direction (175°; 191°; 210°) in MSL condition (UGM-BPPT, 2006).

As shown in Figure 8, the direction of the wave produces adequate Q is from 175° direction, while the other 2 directions produce inadequate Q. All directions of incoming waves show tendency for providing optimum Q value on specific Ho/Lo which around 0.005 – 0.015. This gives an understanding that stability of wave condition propagating into tapchan also quite influential on the wave stiffeness having less stable large wave and vulnerable to break before reaching the converter.

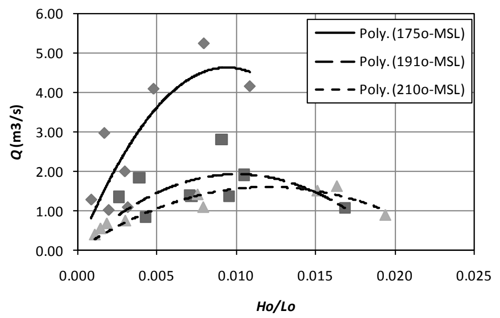

Figure 8. Relationship Q and H_o/L_o for 3 wave direction (175°; 191°; 210°) in MSL condition (UGM-BPPT, 2006).

Water Volume & Reservoir Power

Figure 9 presents a comparison of the water volume captured in the reservoir for 3 kinds of wave directions in variations of T/Ho for MSL condition. Figure 9 shows that the higher and/or the longer the wave length, the greater the water volume entering the reservoir. From 3 kinds of wave direction being examined shows that the incoming wave angle 175° gives the greatest water volume compared to 2 other angles. For example, the maximum water volume captured in 600 seconds for angle 175° is around 800 ltr, for angle 191° around 600 ltr, and for angle 210° is around 200 ltr. This is due to the incoming wave angle 175° is led up closer to the collector mouth than the other 2 angles.

The model test simulation with prototype deep sea wave height (H_o) around 0,3 – 2,5 m with period (T) around 8 – 16 detik produces average discharge value (Q) (MSL condition) for the south incoming wave from the south (175^0) 2,6 m^3/s; for incoming wave from south east (191^0) is 1,62 m^3/s, and for incoming wave from south west (210^0) is 0,95 m^3/s. By comparing the Q value of those three directions, thus the amount of power (P) can be approached by the empirical equation as follows or by curve as shown in Figure 10.

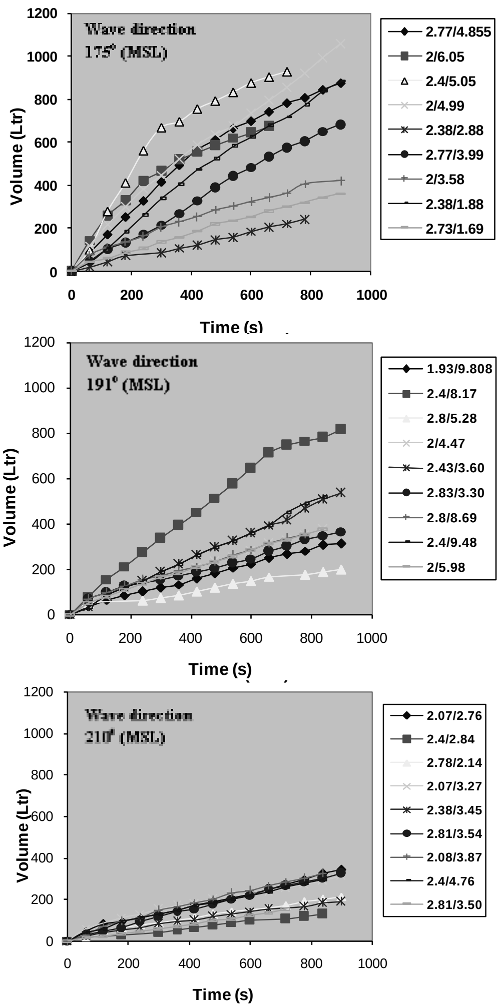

Figure 9. Reservoir production for 3 wave direction (175°; 191°; 210°) in various T and H_o in MSL condition (UGM-BPPT, 2006).

$$P = \frac{A}{\sqrt{h/H_o}} \text{ (kW)} \qquad (28)$$

At value of 2,75 < h < 4,75. A is empirical equation which mainly influenced by condition of Parangracuk bay and the collector shape and the tapchan converter. Value of A = 142 for 175^0; 85,6 for 191^0 dan 52,5 for 210^0.

Tapchan efficiency which is the ratio of Reservoir Power (P) on Energy Flux in the collector mouth (Fe) for all incoming wave directions at the range of wave height and period in the above simulation obtained quite small that is around 1-14% with 7% average. This small efficiency is highly influenced by the collector wall geometric, the alignment of channel direction with the incoming wave direction and the magnitude of wave deformations at the bay. The greater the angle formed by the axes of the channel towards the incoming wave direction, the small the efficiencies can be gained.

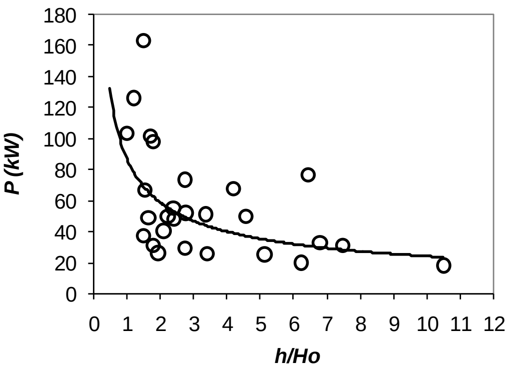

Figure 10. Relationship between height of reservoir relative to incoming wave height (*h/Ho*) and power (*P*) (PSIT UGM-BPPT, 2006).

From the analysis and the description above, it can be recommended the need for planning layout design that can increase the value of efficiency. Hence, the things to be considered in the design are minimizing the influence of the canyon and the collector wall on the magnitude of the reflection wave occurred in the bay and the collector; optimizing the direction, geometric, and the dimension of the tapered channel on the dominant wave direction; the need of the accurate incoming wave distribution data to determine the actual power that can be mobilized with the results of the study model.

CONCLUTIONS

1. Based on the results of the model test simulation with prototype deep sea wave height (H_o) around 0,3 – 2,5 m with period (T) around 8 – 16 detik produces average discharge value (Q) (MSL condition) for the south incoming wave from the south (175^0) 2,6 m^3/s; for incoming wave from south east (191^0) is 1,62 m^3/s, and for incoming wave from south west (210^0) is 0,95 m^3/s.
2. By comparing the Q value of the three directions, the amount of Power (P) can be approached by empirical equation $P = A/(h/Ho)^{0,5}$ where $2,75<h<4,75$. A is empirical equation which mainly influenced by condition of bay and the collector geometric and the tapchan converter. Value of A = 142 for 175^0; 85,6 for 191^0 dan 52,5 for 210^0.
3. The efficiency value is highly influenced by the collector wall geometric, the alignment of channel direction with the incoming wave direction and the magnitude of wave deformations at the bay.

RECOMENDATIONS

From the analysis and discussion above, it is necessary to recommend these considerations as follows:

1. Minimize the influence of the canyon and collector wall on the magnitude of the reflection wave occurred in the bay and the collector;
2. Optimize geometric, the dimension, and the direction of the tapered channel on the dominant wave direction;
3. The need of the accurate incoming wave distribution data to determine the actual power that can be mobilized with the results of the study model

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